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What is the optimal inter-site distance in multi-BS cooperative sensing?

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In the sixth-generation (6G) mobile communication systems, integrated sensing and communication (ISAC) has emerged as a key technology that is promising to be applied in various scenarios such as enhanced positioning, high-resolution imaging, and simultaneous localization and mapping (SLAM) [1]. However, the ISAC-enabled single base station (BS) cannot fulfill its potential and fails to meet the rapidly growing demand for long-range and high-accuracy sensing. In contrast, adopting multi-BS cooperative sensing technology can significantly enhance sensing accuracy and achieve long-range sensing [2].

However, the multi-BS cooperative sensing architecture is inevitable to introduce more interference that may degrade the system performance. To this end, Ref. [3] established a mutual interference model of the multi-BS ISAC system and solved the collaborative precoding problem. Moreover, the inter-site distance can greatly affect the sensing performance, and there is a lack of relevant research in this area. Consequently, we conduct the sensing performance analysis of the multi-BS cooperative sensing system and determine the optimal inter-site distance.

System model. We consider the cooperative sensing scenario with mono-static architecture, where two BSs simultaneously serve an unmanned aerial vehicle (UAV) to improve sensing accuracy. Both BSs are implemented with uniform planar arrays (UPAs) including $N_{\rm t} = N_{{\rm t},x} \times N_{{\rm t},z}$ transmit antennas and $N_{\rm r} = N_{{\rm r},x} \times N_{{\rm r},z}$ receive antennas, with $N_{i,x}$ and $N_{i,z}$ being the numbers of the antennas along x-axis and z-axis for $i \in \{{\rm t},{\rm r}\}$. The two BSs simultaneously transmit sensing signals and receive the passive echo signals carrying the UAV information. We only consider the line of sight (LOS) links between the two BSs and the UAV. BS_1 and BS_2 are located at $(0, 0, h_{\rm BS})$ and $(0, d, h_{\rm BS})$, respectively, where d is the inter-site distance and $h_{\rm BS}$ is the height of the BSs. From a statistical perspective, we assume that the UAV obeys uniform distribution in the cuboid region $\mathcal{D} = [-x_0, x_0] \times [\alpha d, \beta d] \times [h_{\min}, h_{\max}]$, where α and β are the coefficients that denote the horizontal movement range of the UAV. The received echo signals at BS_i interfered with by BS_j for $i, j \in \{1, 2\}, i \neq j$ can be expressed as

$$\boldsymbol{y}_{i,j} = \underbrace{a_i \boldsymbol{A}_i(\theta_i,\phi_i)\boldsymbol{w}_i s_i}_{\text{desired echo signal}} + \underbrace{\sqrt{\rho} b_{i,j} \boldsymbol{G}_{i,j}(\theta_i,\phi_i,\theta_j,\phi_j)\boldsymbol{w}_j s_j}_{\text{echo interference from BS}_j} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{w}_i \in \mathbb{C}^{N_{\rm t}\times 1}$ denotes the transmit precoding of BS_i. $s_i \sim \mathcal{CN}(0, 1)$ denotes the transmit data symbol of BS_i, which is assumed to be independent of each other for $i \in \{1, 2\}$. $\boldsymbol{n} \sim \mathcal{CN}(\boldsymbol{0}, \sigma^2 \boldsymbol{I}_{N_{\rm r}})$ denotes the additive white Gaussian noise. a_i and $b_{i,j}$ denote the coefficients related to the path-loss, radar cross section (RCS) and the total gain. θ_i and ϕ_i are the elevation and azimuth angles of the UAV relative to the BS_i, respectively. $\rho \in (0, 1]$ denotes the coefficient that represents the intensity of the interference. Moreover, we have $\boldsymbol{A}_i(\theta_i,\phi_i) = \boldsymbol{a}_{\rm r}(\theta_i,\phi_i)\boldsymbol{a}_{\rm t}^{\rm H}(\theta_i,\phi_i)$, $\boldsymbol{G}_{i,j}(\theta_i,\phi_i,\theta_j,\phi_j) = \boldsymbol{a}_{\rm r}(\theta_i,\phi_i)\boldsymbol{a}_{\rm t}^{\rm H}(\theta_j,\phi_j)$, with $\boldsymbol{a}_{\rm t}(\theta,\phi)$ and $\boldsymbol{a}_{\rm r}(\theta,\phi)$ being the normalized transmit steering vector and receive steering vector, which can be expressed as

$$\boldsymbol{a}_i(\theta,\phi) = \frac{1}{\sqrt{N_i}} \boldsymbol{a}_{i,z}(\theta,\phi) \otimes \boldsymbol{a}_{i,x}(\theta,\phi), \tag{2}$$

where $\boldsymbol{a}_{i,x}(\theta,\phi) = [1, {\rm e}^{{\rm j}\pi \sin\theta\cos\phi}, \ldots, {\rm e}^{{\rm j}\pi(N_{i,x}-1)\sin\theta\cos\phi}]^{\rm T}$ and $\boldsymbol{a}_{i,z}(\theta,\phi) = [1, {\rm e}^{{\rm j}\pi \sin\theta\sin\phi}, \ldots, {\rm e}^{{\rm j}\pi(N_{i,z}-1)\sin\theta\sin\phi}]^{\rm T}$ for $i \in \{{\rm t},{\rm r}\}$.

Sensing performance analysis. Maximum ratio transmission (MRT) precoding is adopted to enhance the radar signal-to-interference-plus-noise ratio (SINR) as follows:

$$\boldsymbol{w}_i = \sqrt{P_i}\boldsymbol{a}_{\rm t}(\theta_i,\phi_i), \tag{3}$$

where P_i denotes the transmit power of BS_i.

Firstly, we use the larger one of the radar SINRs of BS_1 and BS_2 to evaluate the sensing performance. By defining $\boldsymbol{A}_{{\rm r},i} \triangleq \boldsymbol{a}_{\rm r}(\theta_i,\phi_i)\boldsymbol{a}_{\rm r}^{\rm H}(\theta_i,\phi_i)$ for $i \in \{1, 2\}$, the radar SINRs of BS_1 and BS_2 when the UAV is located at (x, y, z) can be derived as follows (see Appendix A for details):

$$\begin{aligned}\text{SINR}_1(x,y,z) &= \text{Tr}(|a_1|^2 P_1 \boldsymbol{A}_{{\rm r},1}(\rho P_2 |b_{1,2}|^2 \boldsymbol{A}_{{\rm r},1} + \sigma^2 \boldsymbol{I}_{N_{\rm r}})^{-1}) \\ &= \frac{\frac{GCP_1}{(x^2+y^2+(z-h_{\rm BS})^2)^2}}{\frac{\rho GCP_2}{(x^2+(d-y)^2+(z-h_{\rm BS})^2)(x^2+y^2+(z-h_{\rm BS})^2)} + \sigma^2},\end{aligned} \tag{4}$$

$$\begin{aligned}\text{SINR}_2(x,y,z) &= \text{Tr}(|a_2|^2 P_2 \boldsymbol{A}_{{\rm r},2}(\rho P_1 |b_{2,1}|^2 \boldsymbol{A}_{{\rm r},2} + \sigma^2 \boldsymbol{I}_{N_{\rm r}})^{-1}) \\ &= \frac{\frac{GCP_2}{(x^2+(d-y)^2+(z-h_{\rm BS})^2)^2}}{\frac{\rho GCP_1}{(x^2+(d-y)^2+(z-h_{\rm BS})^2)(x^2+y^2+(z-h_{\rm BS})^2)} + \sigma^2},\end{aligned} \tag{5}$$

where $C = \frac{\rm RCS}{f^2} \times 10^{-10.34}$, f denotes the carrier frequency and $G = G_{\rm t}G_{\rm r}$ denotes the total gain. To evaluate the sensing performance statistically, the expectation of radar SINR

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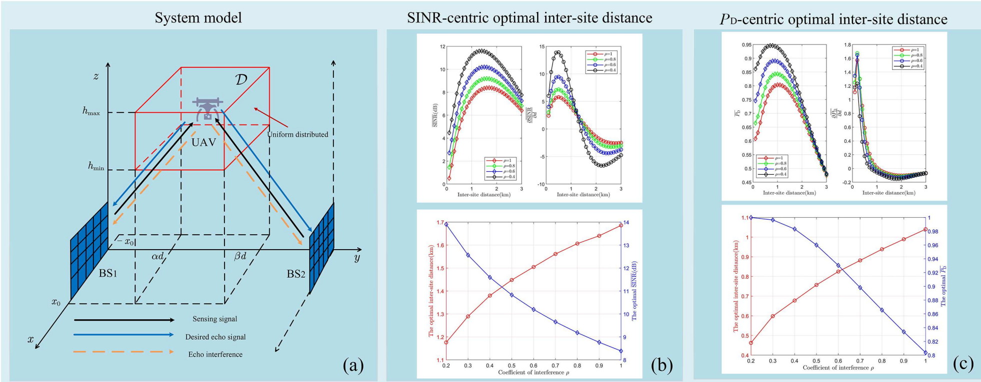

Figure 1 (Color online) System model and simulation results. (a) System model; (b) $\overline{\text{SINR}}$ and $\frac{\partial\overline{\text{SINR}}}{\partial d}$ versus d and the SINR-centric optimal d with different values of ρ; (c) $\overline{P_{\text{D}}}$ and $\frac{\partial\overline{P_{\text{D}}}}{\partial d}$ versus d and the P_{D}-centric optimal d with different values of ρ.

is calculated as follows:

$$\overline{\text{SINR}} = \mathbb{E}\{\max\{\text{SINR}_1(x,y,z), \text{SINR}_2(x,y,z)\}\}$$
$$= \frac{1}{V_{\mathcal{D}}}\iiint_{\mathcal{D}} \max\{\text{SINR}_1(x,y,z), \text{SINR}_2(x,y,z)\}\text{d}x\text{d}y\text{d}z, \tag{6}$$

where $V_{\mathcal{D}}$ denotes the volume of $\mathcal{D}$. Then, we focus on the target detection to obtain fundamental insights into the intrinsic performance of multi-BS cooperative sensing. Specifically, we use the likelihood ratio test (LRT) detector over one sensing block of L symbols. By letting the null hypothesis $\mathcal{H}_0$ denote the absence of the UAV and the alternative hypothesis $\mathcal{H}_1$ denote the presence of the UAV, the detection problem at BS_i interfered with by BS_j can be formulated as the following binary hypothesis testing problem [4]:

$$\begin{cases} \boldsymbol{Y}_{i,j} = \boldsymbol{N}, & \mathcal{H}_0, \\ \boldsymbol{Y}_{i,j} = a_i\boldsymbol{A}_i\boldsymbol{w}_i\boldsymbol{s}_i + \sqrt{\rho}b_{i,j}\boldsymbol{G}_{i,j}\boldsymbol{w}_j\boldsymbol{s}_j + \boldsymbol{N}, & \mathcal{H}_1, \end{cases} \tag{7}$$

where $\boldsymbol{N} = [\boldsymbol{n}(1),\ldots,\boldsymbol{n}(L)]$, $\boldsymbol{s}_i = [s_{i,1},\ldots,s_{i,L}]$ and $\boldsymbol{Y}_{i,j} = [\boldsymbol{y}_{i,j}(1),\ldots,\boldsymbol{y}_{i,j}(L)]$ for $i,j \in \{1,2\}, i \neq j$.

We first determine the threshold according to the value of the probability of false alarm P_{FA} for performing constant false alarm rate detection [5], and then derive the expression of detection probability of BS_i interfered with by BS_j as follows (see Appendix B for details):

$$P_{i,j}(x,y,z) = Q\left(\kappa - \sqrt{2L\left(\text{SINR}_i(x,y,z) + \frac{\rho P_j|b_{i,j}|^2}{\rho P_j|b_{i,j}|^2+\sigma^2}\right)}\right), \tag{8}$$

where $\kappa = Q^{-1}(P_{\text{FA}})$. In the multi-BS cooperative sensing scenario, BS_1 and BS_2 simultaneously detect the UAV to enhance the precision of detection. Thus, the joint detection probability can be calculated as follows:

$$P_{\text{D}}(x,y,z) = 1 - (1 - P_{1,2}(x,y,z)) \cdot (1 - P_{2,1}(x,y,z)). \tag{9}$$

Similarly, the expectation of the joint detection probability is calculated as follows:

$$\overline{P_{\text{D}}} = \mathbb{E}\{P_{\text{D}}(x,y,z)\} = \frac{1}{V_{\mathcal{D}}}\iiint_{\mathcal{D}} P_{\text{D}}(x,y,z)\text{d}x\text{d}y\text{d}z. \tag{10}$$

Then we calculate the partial derivatives of the two sensing metrics with respect to d (see Appendix C for details) and adopt the bisection method to obtain the optimal inter-site distance.

Simulation results. Parameters of the simulation are set as $f = 4.8$ GHz, $\sigma^2 = -95$ dBm, RCS $= 0.01$ m^2, $\alpha = 0.1$, $\beta = 0.5$, $N_{\text{r},x} = N_{\text{t},x} = 16$, $N_{\text{r},z} = N_{\text{t},z} = 24$, $P_1 = P_2 = 58$ dBm, $G_\text{t} = G_\text{r} = 22.5$ dB, $P_{\text{FA}} = 1\%$, $h_{\text{BS}} = 30$ m, $x_0 = 200$ m, $h_{\min} = 100$ m and $h_{\max} = 300$ m. Due to symmetry, we only consider the case where the UAV is closer to BS_1. The SINR-centric and P_{D}-centric optimal inter-site distance with different values of ρ are illustrated in Figures 1(b) and (c), respectively. It is apparent that the optimal inter-site distance increases with the coefficient of interference and the optimal sensing metrics have an opposite trend.

Conclusion. This study investigated the multi-BS cooperative sensing scenario, where the echo interference between BSs was considered. The closed-form expressions of radar SINR and joint detection probability were derived. We also obtained the optimal inter-site distance, aiming to enlighten the deployment of the cooperative sensing network.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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